HOHLRAUM RADIATION-DRIVE MEASUREMENTS ON THE OMEGA LASER

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Introduction

In the laser-driven, indirect-drive fusion scheme,[1] laser beams are focused through the laser entrance holes (LEHs) onto the inside wall of a high-*Z* enclosure (hohlraum). The laser light is absorbed and converted into soft x rays that fill the hohlraum. These x rays heat a target capsule in the center so rapidly that ablation of the outer surface occurs. The rocket-like outward expansion of this material causes a reaction—an inward implosion of the remaining capsule material. For this reason, the x-ray radiation is referred to as the drive. Detailed knowledge of the radiation drive is of great interest and has been the objective of many hohlraum experiments over the last decade.[2–6] The radiation is often characterized by a radiation temperature, T_r, which is defined by equating the total frequency-integrated radiation flux to a blackbody flux, $\sigma(T_r)^4$, where σ is the Stefan–Boltzmann constant.

Time-dependent radiation temperatures have been measured extensively on Lawrence Livermore National Laboratory's Nova[7] laser using an absolutely calibrated, filtered diode array called Dante.[8,4,9] In the Nova experiments, the Dante diagnostic was set up to measure the radiation flux emerging from a hole in the side of a hohlraum with a Dante angle (θ_D in Figure 1) of 90°. Because this method only measures the radiation flux coming off the indirectly heated wall opposite the hole, the flux must be divided by the wall's effective reflectivity, or albedo, to obtain the true radiation temperature near the wall.[4,9] The albedo depends upon the material opacity, which varies with time, and must be calculated analytically or numerically. Although the peak temperatures measured through the "side holes" agree well with simulations,[9] at early times the simulations underestimate the drive. This discrepancy has been attributed to

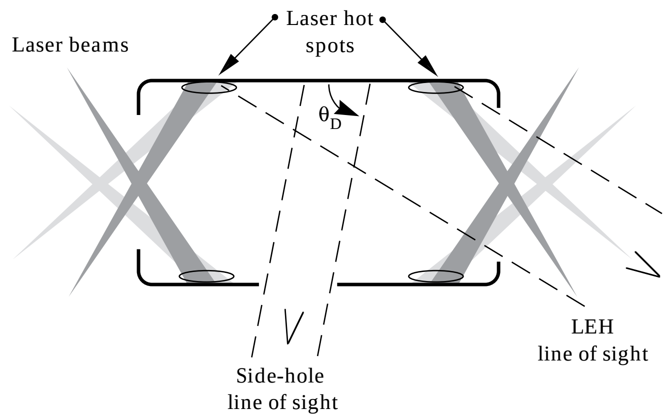

FIGURE 1. A typical laser fusion hohlraum showing the Dante diagnostic's lines of sight through the side hole and the LEH. (50-00-0598-1159pb01)

uncertainties in the low-temperature opacities, and to scattered or reflected laser light hitting that part of the wall being measured.

The opacity is determined using an average atom model called XSN.[10] At high temperatures (>200 eV), the wall losses modeled with XSN are quite close to those calculated with the more sophisticated STA[11,12] model and with experiments.[13,14] However, XSN opacity multipliers of 1.5 are needed to agree with the STA estimates at lower temperatures (<150 eV).[15] The early time drive can also be recovered using a 1.5 multiplier on the XSN opacity and allowing 10% of the laser light to strike the wall, or by using a factor-of-three multiplier with no incident laser light.

Recently, proof-of-principle hohlraum experiments have been done at the Laboratory for Laser Energetics' Omega laser facility. As many as 40 of Omega's 60 beams irradiated Nova-scale hohlraums with up to 20 kJ of 351-nm wavelength light, delivered in a 1-ns flat-top pulse.[16,17] Unlike experiments on Nova with a single

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laser cone at an angle of 50° relative to the hohlraum axis, the laser beams for these experiments were distributed into three cones at angles of 21°, 42°, and 59°.

Thin-wall hohlraums were used to limit debris in the chamber and to allow both the laser spots and the imploded cores to be imaged.[18] These hohlraums were constructed with 2-μm Au interior walls with a 100-μm-thick CH external overcoat for structural support. Their inside diameters were 1600 μm; their lengths varied from 2100 to 2800 μm, and some had a 500-μm-diam diagnostic hole drilled through their side.

In this article, we report on drive measurements and present 2D LASNEX[19] simulations of these experiments. (Details about hohlraum simulations with LASNEX can be found in Reference 5.) In order to link this work to previous Nova experiments, we used the traditional side-hole technique,[4] and also measured the radiation flux through the LEH for the first time. Our experimental results and simulations indicate that the drive measurements made through the LEH are superior to those done through the side-hole. There is good agreement between the LEH experimental data and the simulations. In particular, the early time discrepancy seen in previous Nova experiments is no longer there. Furthermore, our simulations suggest that the radiation flux emerging from the LEH might be more representative of the drive on the capsule, because the line of sight through the LEH sees both the wall and the laser hot spots (Figure 1) as the capsule does, whereas the side hole's line of sight only allows sampling the indirectly heated wall.

Experiments

The Dante diagnostic,[8] which measures the radiation flux, is a ten-channel array of absolutely calibrated x-ray vacuum photodiode detectors combined with Al, Cr, and Ni photocathodes. Various thin filters and grazing-incidence mirrors are placed in front of the detectors, giving each channel a significant response in different parts of the spectrum. The spectral coverage ranges from 50 eV to 3000 eV, and the diodes' outputs are recorded on 5-GHz bandwidth oscilloscopes. The system has a temporal response on the order of 200 ps. The data is analyzed (at 100-ps intervals) to find a smoothed spectrum that is consistent with the signal from each channel. Because the channels have some overlap in their spectral coverage, the task of smoothing the spectrum is well constrained. While some variation is possible in the details of the spectrum (by varying the amount of smoothing allowed), the integral over all energies changes little with these variations. As mentioned earlier, this flux (watts per steradian [W/sr] from a hole of known area and view angle) is conveniently characterized by a radiation temperature T_r, even though the smoothed spectrum is not necessarily Planckian (as shown later). To ensure that the Dante diagnostic was collecting radiation only along the direct line of sight and that a negligible amount of radiation was reaching it through the thin Au walls, shots with hohlraums having no diagnostic side hole were also measured from the side.

For some drive measurements, the radiation temperature was measured through the side hole ($\theta_D = 79°$ in Figure 1). The hohlraums used were 2800 μm long and were shot with 15 kJ of energy, using the two laser cones at 42° and 59°. Because T_r was only measured through the side hole in the Nova shots, Nova experiments complementary to those done with Omega (using identical thin-walled hohlraums at a similar laser power) were also done. The T_r measurements for the Omega and Nova thin-walled hohlraums and the simulated temperatures are shown in Figure 2.

The 10-eV difference between the Omega and Nova shots is due to beam-pointing differences. This difference is predicted both by the simulations and by simple view-factor calculations. The T_r measured on Omega is colder, because the laser spots are further from the midplane area viewed by Dante. The simulations for the thin-walled hohlraums are similar at early times to those done previously for thick-walled (25-μm Au-wall) Nova hohlraums[9] in that they also underestimate the temperature. However, we also found that the peak temperatures from the thin-walled hohlraums from both Omega and Nova were consistently 10 to 20 eV below their predicted values. This result contrasts with that for the thick-walled Nova hohlraums, where the simulated peak T_r was always within a few eV of the experiment.[4,9]

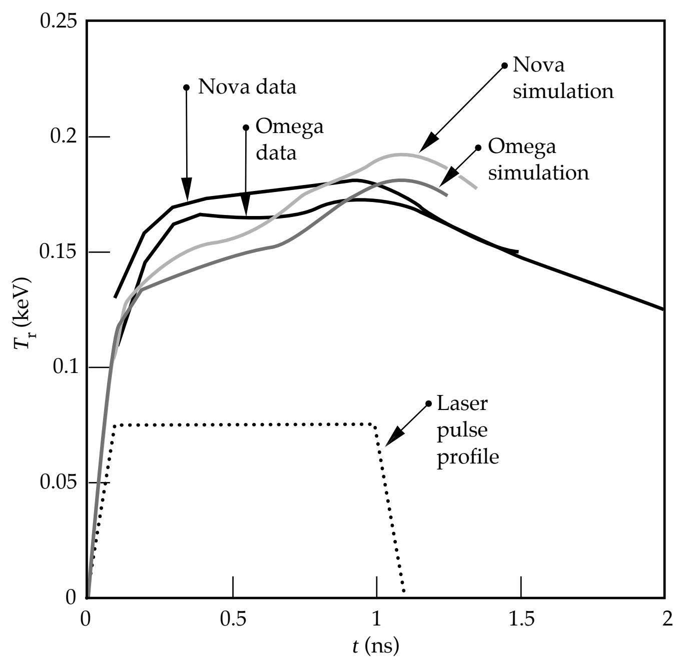

FIGURE 2. Radiation temperatures of Omega and Nova experiments taken from the hohlraums' side-hole line of sight (black lines) and the corresponding LASNEX simulations (gray lines). (50-00-0598-1160pb01)

From these thin-walled hohlraum experiments, it might appear that they are cooler than their thick-walled counterparts.[4,9] However, simulations for hohlraums with Au wall thickness of 2 µm and 25 μm give identical radiation temperatures. This result is consistent with previous simple estimates[1] showing that the burn-through time for 2 μm of Au, at T_r = 200 eV, is on the order of 2 ns, which is longer than the laser pulse's duration. Moreover, as we will show, temperatures measured through the LEH are indeed as hot as predicted.

We now believe that the discrepancy in peak T_r, as measured through the side-hole, is due to the way the holes were fabricated rather than to the wall thickness. For the thick-walled hohlraums used in previous Nova experiments, the side holes were lined with Be washers to prevent them from closing up. In contrast, the side holes on the thin-walled hohlraums were not lined. They were simply drilled straight through, which makes the hole more susceptible to closure and tunnel obstruction effects.

Experiments on Nova were recently done with thick-walled hohlraums having holes constructed in the same way as those of the thin-walled hohlraums. Their peak temperatures were also consistently 10 to 12 eV below predictions. These experiments clearly showed that how the hole is fabricated has an effect on the measurements.

However, rather than dwelling on improvements to the diagnostic side hole, we decided to investigate a new method of measurement. We chose to measure the radiation temperature through the LEH.

Due to the "soccer ball" symmetry of Omega,[20] many hohlraum orientations give an identical laser irradiation pattern. In one orientation, the Dante diagnostic viewed the hohlraum through the LEH at an angle of 37.4°. Besides measuring a flux that is more representative of the capsule drive, other practical advantages result from this measurement technique:

- Because the LEH is 2.5 times larger than the diagnostic hole, hole closure should be a less significant problem.
- The LEH viewing method is less invasive; a hole in the side of the hohlraum disturbs the cylindrical symmetry (which is amenable to 2D modeling) and adds to the radiation losses.
- The laser-heated blowoff seen through the LEH is hotter and less dense than the blowoff seen through the side hole; it should therefore be more transparent to the x-ray radiation that we are measuring.
- Typically, the capsules block Dante's view of the wall across from the side hole, but LEH measurements can be made simultaneously with the implosions.
- Viewing the laser hot spots gives better measurements of hard x rays.

Comparison to Simulations

Figures 3a and 3b show the radiation temperatures as measured through the LEH (along with the corresponding simulation data) for a 2100-µm- and a 2300-μm-long hohlraum, respectively. Each shot had an energy of 15 kJ, but with 42° and 59° cone angles, respectively. There is good agreement between simulation and experimental data over the duration of the laser pulse. In particular, there is good agreement at early times. At 300 ps, the simulated and measured temperatures agree to within 5 eV. By comparison, there is a 20-eV discrepancy when the temperature is measured through the diagnostic hole in the side of the hohlraum, as described in the previous section. The insert in Figure 3b plots a typical measured spectrum, showing its non-Planckian distribution due to line emission in the coronal plasma.

The good agreement during the laser pulse between measurements through the LEH and the simulations indicates that we are accurately modeling the physics of the laser hot spot. When viewing the 2100-μm-long hohlraum at 37° through the LEH, we "see" six laser spots. These spots constitute 28% of the wall area under observation, which, in turn, equals 12% of the interior surface. However, simulations show that at $t = 300$ ps these laser hot spots account for over 70% of the flux. Therefore, at early times the radiation flux seen by the capsule and through the LEH is dominated by the laser-irradiated hot spots. At peak drive, the flux from the indirectly heated wall exceeds that from the hot spots. There is still good agreement up to 1.3 ns, because the indirectly heated wall is hot and correctly modeled.

Beyond this time, modeling and experiment diverge. However, with arguments based on energetics, it is difficult to explain how a hohlraum could continue to cool so rapidly. For this reason, we suspect that this late time discrepancy might be related to opacity modeling in the rapidly cooling plasma accumulating at the LEH. Indeed, more sophisticated opacity models[11] show that the plasma in the LEH becomes more opaque in the thermal x-ray region than is predicted by the XSN model used in the simulations.

The good agreement between experiment and simulation is also seen for longer-duration, shaped laser pulses. In order to study time-dependent symmetry, several shots were done with a 2-ns stepped, shaped pulse. For these shots, the Dante diagnostic measured the radiation temperature through the LEH. In Figure 4, we show these measurements, along with the data from corresponding simulations. The shape of the laser pulse is shown in Figure 4a. For these longer pulses, there is sufficient time for the Au plasma ablating from the wall to fill the hohlraum.

LASNEX simulations indicate that electron densities between 10 and 20% of the critical density for 0.351-µm light (9×10^{21} cm^{-3}) are achieved. As a result of this plasma filling, there was a substantial

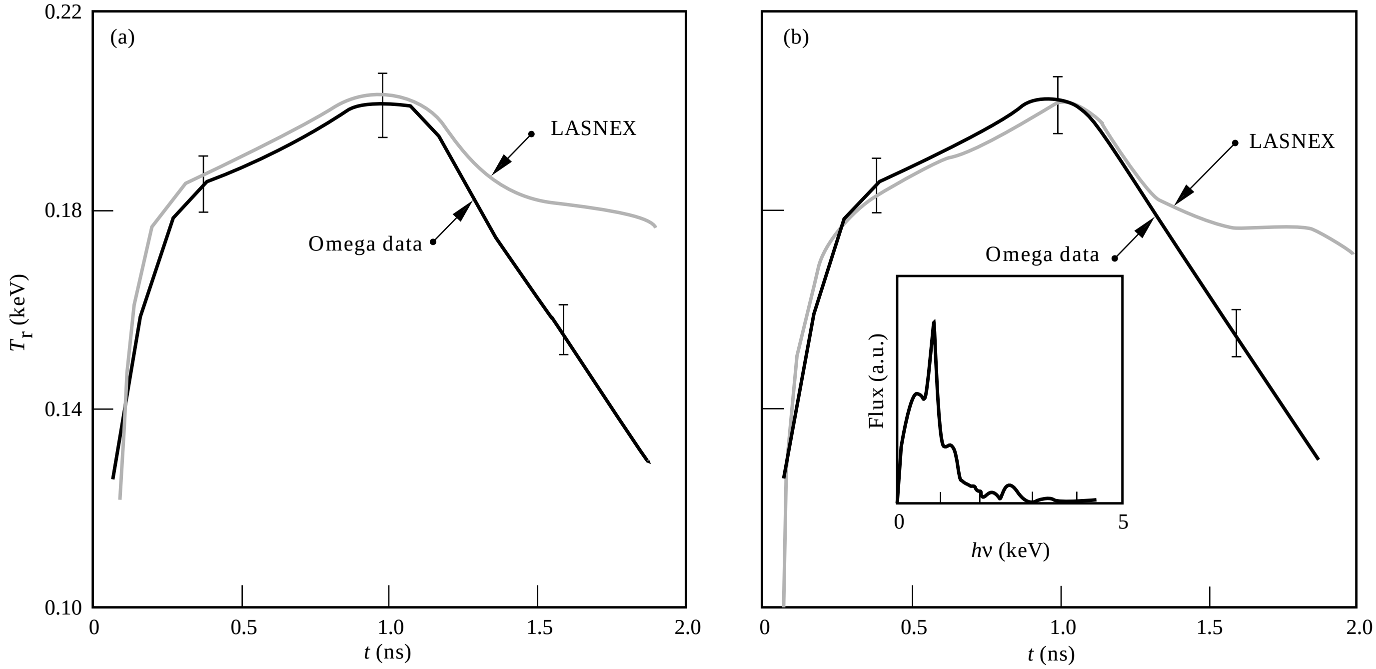

FIGURE 3. Radiation temperature seen through the LEH (black line) and the corresponding LASNEX simulations (gray line) for hohlraum lengths of (a) 2100 μm and (b) 2300 μm. (The error bars show the 3% uncertainty in T_r that is typical for Dante measurements.) Insert in (b): spectrum of the radiation flux at 1.0 ns. (50-00-0598-1161pb01)

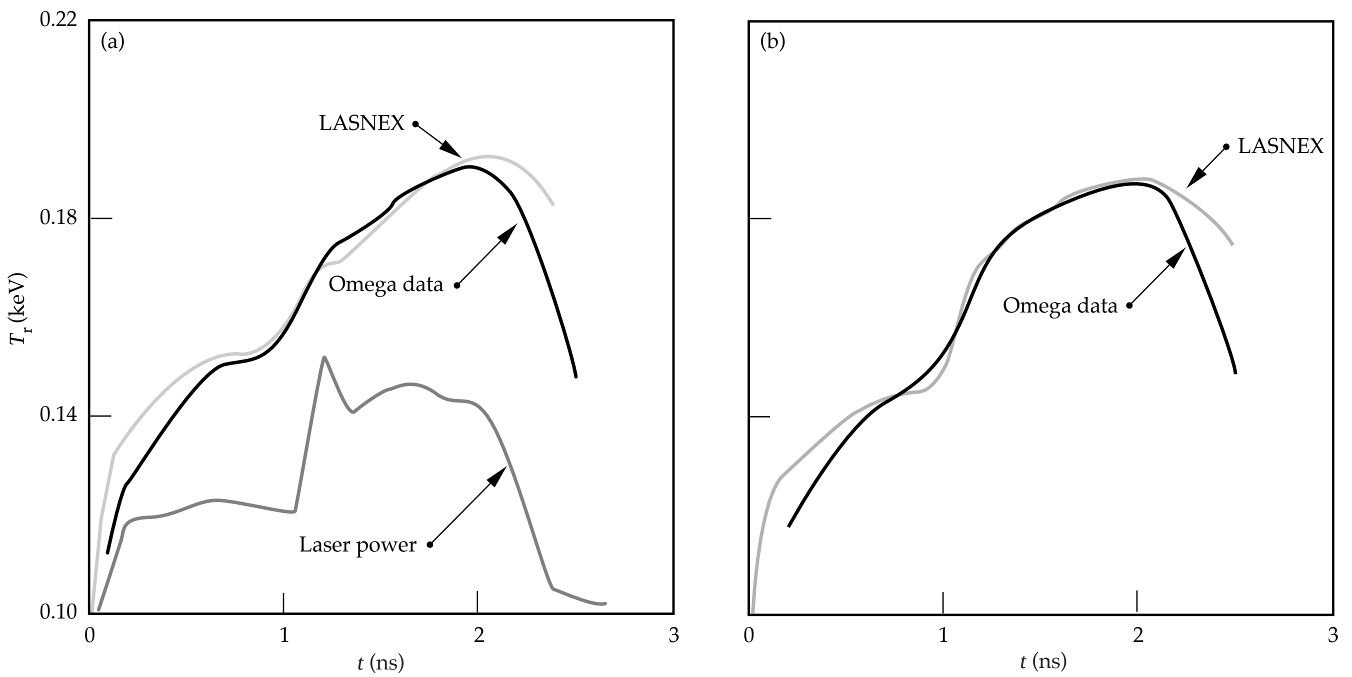

FIGURE 4. Radiation temperature seen through the LEH (black line) along with the LASNEX simulation (gray line) for stepped, shaped laser pulses. The hohlraum lengths are (a) 2100 μm and (b) 2200 μm, respectively. The laser power, shown as the dark gray line in (a), is given in arbitrary units to show the pulse shape. (50-00-0598-1162pb01)

amount of measured stimulated Brillouin scattering (SBS) backscatter (10 to 20%). By comparison, the backscatter levels for the 1-ns pulses were always below a few percent. In the simulations, we reduced the incident laser power consistent with the measured backscattered levels over the second nanosecond of the laser pulse. Once again, as shown in Figure 4, there is a good agreement between the experiments and simulations.

Analysis of the LEH Line of Sight

We now examine how the radiation flux on the capsule compares to that emerging through the LEH in simulations. Consider a 2100-μm-long hohlraum being driven by 15-kJ laser at cone angles of 42° and 59°. In Figure 5 we have plotted the simulated temperatures of the flux on the capsule, of the flux through the LEH at 37.4°, of the flux through the side hole, and of the total flux (integrated over all angles) leaving the LEH. Our plot shows that the total LEH flux provides the measurement closest to the actual capsule drive. Next closest is the single line-of-sight LEH measurement at 37.4°, which is a bit higher than the capsule flux—but much closer than the single line-of-sight measurement made through the side hole.

In general, inferring true capsule drive from measurements made along any single line of sight requires albedo/geometry corrections. However, the simulated and experimental temperatures are in much better agreement for the LEH line-of-sight measurement, and it requires less correction than does the side-hole line of sight. For these reasons, we believe that temperature measurements through the LEH are more representative of the drive on the capsule.

Finally, we looked at the angular dependence of the radiation flux [~$(T_r)^4$] through the LEH. In Figure 5, the black lines in the insert are polar plots of the intensity per steradian (I/sr) of the radiation emerging from the simulated LEH (in arbitrary units) at 300 ps and 1 ns. For contrast, the gray lines show the Lambertian I/sr with the same integrated power (171 eV and 199 eV). A Lambertian intensity assumes a uniform wall temperature; the angular dependence comes from the projected area of the hole.

At small polar angles, where the diagnostic views the opposite LEH, the simulated LEH's I/sr is much less than the equivalent Lambertian. The intensity rises rapidly as the LEH line of sight begins to view an admixture of re-emitting wall and hot spots. The simulated I/sr then drops roughly as the cosine of the polar angle (cos θ), since the projected area of the LEH decreases at larger angles.

At later times, when the wall albedo has risen and the emission is not so dominated by hot spots, the I/sr at angles greater than 25° from the polar axis is approximately Lambertian. Consequently, measurements made from any larger angle would provide fairly representative data about the total radiation energy escaping from the LEH.

At earlier times, when the hot spots dominate, the I/sr has more structure. A better diagnostic technique for measuring the capsule drive, especially at earlier times, would be to measure emission at several angles, thereby allowing us to properly perform the angular integration. We have long-term plans to develop such a diagnostic array.

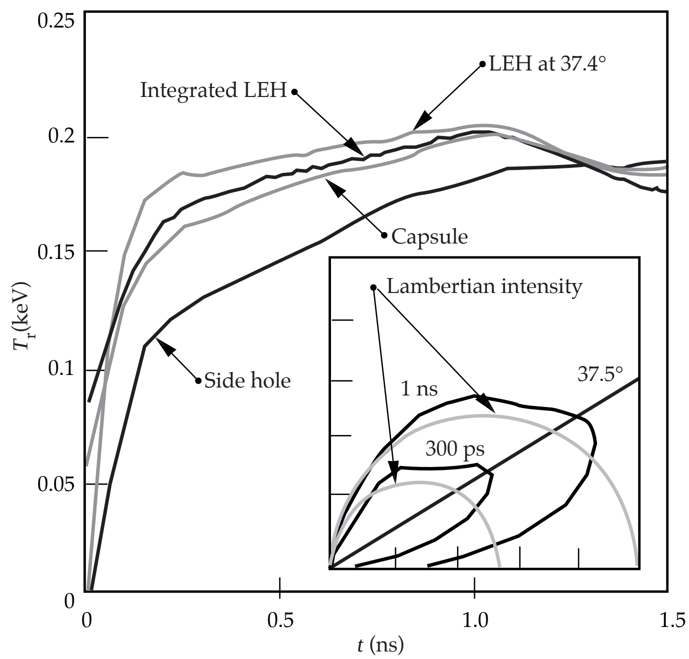

FIGURE 5. A simulation of the flux $T_r(t)$ onto the capsule compared to the flux as seen through the LEH at 37.4°, the total flux out of the LEH (integrated over all angles), and the total flux through the side hole. Insert: The radiation flux out of the LEH (in arbitrary units) vs the viewing angle, at two times, in polar coordinates. The equivalent Lambertian fluxes (light gray lines) are also shown.
(50-00-0598-1163pb01)

Conclusions

Measuring the radiation drive through the LEH appears to be a much better diagnostic of the drive than is measuring through a side hole. At the LEH, hole closure, uncertainties in the low-temperature opacity, and stray laser light do not appear to be the problems they are at the side hole. Moreover, the raw (uncorrected) temperature is more representative of the capsule drive. We plan to develop this method further to allow measuring future hohlraums, such as those that will be used at the National Ignition Facility.

Acknowledgments

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